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Norway's electric vehicle revolution: unveiling greenhouse gas emissions reductions and material use of passenger cars across space and time

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Abstract

Electric vehicles (EVs) are a key strategy for mitigating greenhouse gas (GHG) emissions from personal mobility. Norway's strong EV supporting policies has led to an explosion of EVs and reduced direct emissions, but with rural-urban differences and undocumented upstream impacts. We investigated how the material composition and life cycle GHG emissions of Norwegian vehicles have evolved between 2000 and 2023 by integrating spatiotemporal vehicle data with a vehicle life cycle assessment model. The average life cycle GHG emissions per vehicle-km (vkm) of a newly registered car have significantly decreased (−49% since 2000) thanks to the decrease in use phase emissions (−89% since 2000). However, component-related emissions have increased (+81% since 2000) due to electrification and a trend towards large vehicles. Changes in the fleet are slow: EVs constituted 24% of the stock in 2023 and average life cycle GHG emissions per vkm have barely declined (−8% since 2000). EVs are concentrated in urban and peri-urban areas, while remote areas have few EVs, illustrating the unequal spatial distribution of electric mobility. Our study highlights the challenges related to EV penetration and emphasizes the need to expand to additional indicators beyond direct GHG emissions for a comprehensive understanding of EVs' role in climate change mitigation.

1. Introduction

In 2019, about 23% of global energy-related direct CO_2 emissions were from transport activities, with 70% of these coming from road transport [1]. Transport relies heavily on fossil fuels (in 2022, ≈95% of its final energy use came from oil and natural gas derivatives [2]). With no tailpipe emissions, electrification of the vehicle fleet is a key option for decarbonizing personal mobility in-line with stringent climate change mitigation scenarios that limit global warming below 2 °C in 2100 [1, 3, 4].

Referred as 'the [electric vehicles (EVs)] capital of the world' with EVs 'everywhere' [5], Norway makes the headlines of newspapers. Already in 2013, it was called the 'electric car heaven' [6] and has been seen as a pioneer in EVs adoption ever since [7–9]. The implementation of measures encouraging EV adoption (e.g. exemption from value-added tax, use of bus lanes, free parking) has led to a 88.9% share of EVs in the 2024 sales statistics [10, 11]. A milestone in Norwegian EV history was reached in September 2024, when more EVs were registered than gasoline cars [12].

Norway's high share of EVs presents an opportunity to study the leading factors for EV adoption, as well as the benefits and trade-offs. Households with higher income, wealth, and education [13, 14], living in urban areas with children [14], or with greater availability to public charging stations [15] are more likely to own or adopt an EV. Passenger cars' CO_2 emissions in Norway decreased because of the shift to EVs. The advantageous taxation system facilitated this shift [16], and future EVs' adoption might be slowed if the tax exemptions were to be suddenly withdrawn, potentially compromising short-term emission targets [17]. Decreasing territorial emissions is the immediate concern to achieve the 55% cut of greenhouse gas (GHG) emissions by 2030 compared to 1990 (Norway's climate target under the Paris Agreement [18]). However, understanding the climate mitigation potential and trade-offs of EVs requires taking a life cycle perspective. Upstream GHG emissions, which can occur abroad, arise from the material consumption and battery production [19, 20] induced by EV penetration, which affects the environmental performance of driving. However, material composition and life cycle GHG emissions of the Norwegian car fleet is still underexplored.

Here we study the historical (2000–2023) Norwegian car fleet by integrating spatiotemporal vehicle data based on the Norwegian vehicle register [21, 22] with vehicle material archetypes [23], and a vehicle life cycle assessment model (*carculator* [24–26]). We quantify the evolution of the material composition and life cycle GHG emissions, thereby evaluating the role of EVs in reducing passenger vehicles' GHG emissions in Norway. We present EV penetration rates, average material composition and life cycle GHG emissions over time, and highlight spatial differences in vehicle stock distribution among and within Norwegian municipalities.

2. Methods

2.1. Historical stock of passenger cars

We collected historical stocks of passenger cars from (1) a high spatial resolution database (Geodata Online) of individual passenger cars in 2022 with their powertrain, gross weight, and model year [21], and (2) microdata.no, an online platform to access and process Norwegian microdata, including passenger vehicles between 2000 and 2023 [22]. We generated three datasets based on data extracted from microdata.no (available on Zenodo [27]): (dataset 1) number and average curb weight of vehicles grouped by municipality and powertrain; (dataset 2) number and average curb weight of vehicles grouped by size (for material composition in section 2.2), powertrain and first registration year; (dataset 3) number of vehicles grouped by size (for life cycle GHG emissions calculations in section 2.3), powertrain, first registration year and size of municipality. Before 2016, gasoline hybrids were manually adjusted as these were not properly registered in microdata.no. Details about the data collection and processing are available in SI S1.

2.2. Material composition

We calculated the weighted average curb weight of vehicles at the national scale using curb weight averages of the processed passenger vehicles data (dataset 2 from microdata.no) and derived the average material composition using the material composition of archetypes of passenger vehicles (formulas detailed in section S3 in SI S1). These archetypes, developed in the Circular Economy Modelling for Climate Change Mitigation (CIRCOMOD) project, represent vehicles' material composition (14 materials) according to the powertrain (battery electric, internal combustion engine (ICE), and plugin hybrid), size (mini, small, medium, large, extra-large) and cohort (2005, 2010, 2015, 2020, 2025) [23]. We used linear interpolation to estimate the material composition of vehicles produced in the years in between.

2.3. Life cycle GHG emissions

We used *carculator*, a parameterized model estimating a range of midpoint and endpoint environmental impact indicators per vehicle-km (vkm) of passenger vehicles [24–26]. With *carculator*, we calculated life cycle GHG emissions (100 year global warming potentials emission metrics from the Intergovernmental Panel on Climate Change [28]) for a set of archetypical vehicles depending on powertrain (battery electric, diesel, gasoline, plugin and non-plugin hybrids), size category (mini, small, lower medium, medium, large, and large SUV), and manufacture year (between 2000 and 2023). We considered a Norwegian electricity mix (largely based on hydropower [29]) for vehicle operation. For other parameters, we used the default *carculator* values, such as a lifetime of 200 000 km and an annual mileage of 12 000 km (details provided in SI S1). Geodata and microdata.no do not distinguish between hybrid and plugin hybrid. Therefore, we adjusted life cycle GHG emissions from *carculator* to account for the share of hybrid and plugin hybrid [30].

We applied the life cycle GHG emissions from *carculator (*formulas detailed in section S3 in SI S1): first, to the individual vehicles from Geodata for detailed geospatial analysis, and then, to the stock of vehicles from microdata.no (dataset 3) to calculate life cycle GHG emissions for an average vehicle at national and municipal category scales between 2000 and 2023. Life cycle stages covered included the manufacture of the vehicles' components (glider, powertrain, energy storage), the vehicles' maintenance, their use phase (energy chain, direct exhaust, direct non exhaust) and their end-of-life. Life cycle GHG emissions can be presented: (1) per vkm, where emissions are distributed across the expected lifetime in kilometers and can be used to calculate fleet-average emissions; (2) per estimated yearly emissions such as component-related emissions (glider, powertrain and battery) of newly registered vehicles or use-phase related emissions of the fleet.

We used the stochastic mode of *carculator* (based on Monte-Carlo analysis) to estimate uncertainties of GHG emissions: for each archetype in the set of archetypical vehicles, 100 iterations are performed, and the 5th and 95th percentiles form lower and upper bounds of uncertainty ranges.

2.4. Spatial analysis and socio-economic variables

To evaluate vehicle stocks (average curb weight and average life cycle GHG emissions) and the adoption of EVs between 2000 and 2023 at the municipal level, we grouped municipalities into categories: less than 5000, 5000–10 000, 10 000–20 000, 20 000–50 000, and more than 50 000 inhabitants excluding Oslo, Bergen and Trondheim, which we looked at individually. Norwegian municipalities cover a wide range of population size. In this study, this categorization enables highlighting urban-rural differences.

Using the most recent refined geospatial data (2022), we performed a statistical analysis to provide insights into the drivers of personal mobility decarbonization. We measured correlations between several variables using the Pearson correlation coefficient, including average income [31], population density, and the distance to a large municipality (estimated based on Geodata Online [32, 33]), defined with a population larger than 50 000 inhabitants.

3. Results

3.1. Norwegian car fleet analysis

Until 2012, most newly registered cars were ICE vehicles (figure 1(a)). Electric and gasoline hybrid vehicles adoptions began in 2012 whilst sales of ICE vehicles were decreasing. Between 2016 and 2021, the share of gasoline hybrids among newly registered cars stayed between 24%–30%, but the share of EVs continued to increase to reach more than 80% in 2023.

The share of heavy cars has been increasing compared to the early 2000s, when most cars were lighter than 1500 kg (figure 1(b)). Heavy vehicles (>2000 kg) represented more than one third of newly registered cars in 2021 and half in 2022 and 2023. This led to an increase in the average curb weight from 1200 kg in 2000 to about 2000 kg in 2022–2023 (figure 1(c)). On 1st of January in 2023, a weight tax was introduced [34]. While its effects are not yet clearly notable, the increasing weight trend stopped between 2022 and 2023.

Heavier vehicles are associated with higher material requirements, as reflected in the life GHG cycle emissions (figure 1(d)). Even though average life cycle GHG emissions per vkm have been decreasing since 2008 (from ≈294 gCO_2-eq in 2008 to ≈144 gCO_2-eq in 2023) due to a decrease in direct exhaust and energy chain emissions (−89% since 2000), the component-related emissions have increased by 81% since 2000. The emissions from EV batteries (resource extraction and battery production) represented up to 18% of the life cycle GHG emissions of newly registered cars in 2023.

Despite the increasing use of aluminum for lightweighting purposes (figure 1(c)), the average curb weight of cars has increased during the study period (figure 2(a)). All powertrain types were affected, but EVs gained the most weight. EVs' GHG emissions per vkm have also increased but have stayed well below those of other powertrains (figure 2(b)). The average curb weight of newly registered ICE vehicles and EVs has increased faster than the life cycle GHG emissions per km driven, most likely due to improvements in car manufacturing and emissions regulations. This increasing average curb weight reveals an increasing use of resources.

Figure 3 presents Norwegian car fleet changes since 2000. While 80% of the newly registered cars in 2023 were electric, the car fleet changed slowly, with EVs representing 24% of the fleet in 2023 (figure 3(a)). With the stock shifting towards heavier vehicles (figure 3(b)), the average curb weight is steadily increasing (figure 3(c)), and the average life cycle GHG emissions have not changed significantly (figure 3(d)). Average life cycle GHG emissions in 2023 are only 8% lower than in 2000. Although the direct exhaust and energy chain emissions decreased by 21% between 2000 and 2023, the component-related emissions increased by 37% to represent nearly one-third of the life cycle GHG emissions in 2023.

3.2. Geospatial analysis

EVs are adopted at different rates in different regions (figure 4(a)). The rates are highest in Bergen and Oslo, followed by Trondheim and other municipalities with >50 000 inhabitants. Other categories of municipalities by population are below the national average. However, there are municipalities with higher shares of EVs than the large municipalities, as demonstrated by the light blue area. For instance, Askøy, a municipality close to Bergen with nearly 30 000 inhabitants, had Norway's largest share of electric cars in 2023 (45%). Vehicles whose location is unknown ('unknown municipality'), mostly owned by companies/organizations, also present a high rate

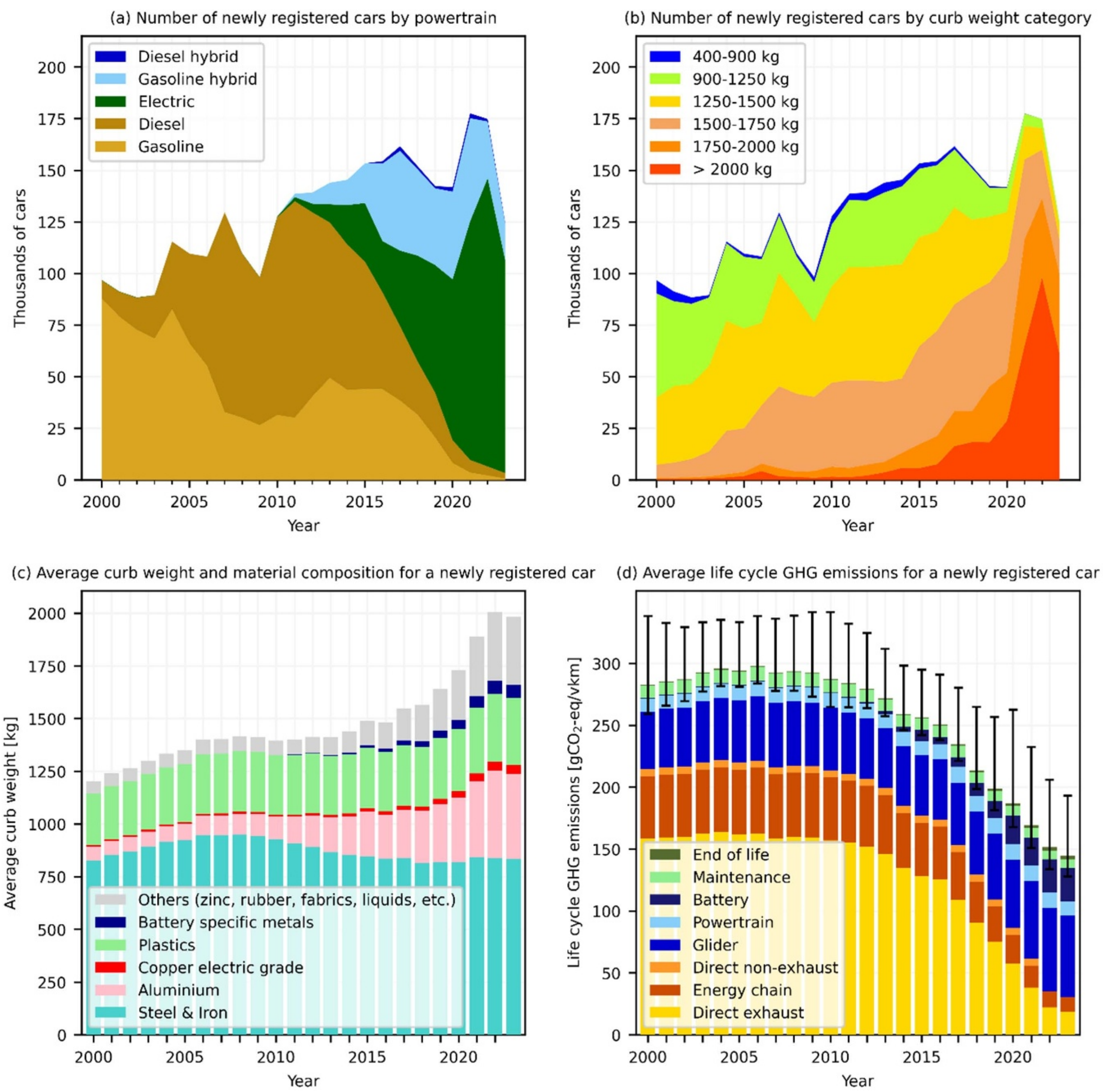

Figure 1. Description and characteristics of newly registered cars between 2000 and 2023 in Norway: (a) number of newly registered cars by powertrain, (b) number of newly registered cars by size (the bottom value of the range is excluded except for the first range 400–900 kg, the top value of the range is included), (c) average curb weight and material composition for a newly registered car, (d) average life cycle GHG emissions for a newly registered car. Note: before 2016, we made manual adjustments of hybrid vehicles as these were not properly registered.

of electrification. These cars represent around 10% of the fleet and, together with cars located in large municipalities, contribute to increasing the average share of electric cars in the country. One quarter of the vehicle fleet in Norway was electric in 2023, but the median across all municipalities was 13% (i.e.), 50% of the municipalities still had less than 13% of EVs in their stock. The lowest EV shares are found in the North of Norway (Troms, Finnmark, Nordland) and in Innlandet (figure 4(b)).

Across the categories of municipalities, the average curb weight of vehicles has been following a similar increasing trend (figure 4(c)), indicating that electrification is not necessarily the main driver for increasing car weights. The few municipalities with low average curb weight are in the south of the country (figure 4(d)).

Even though the average curb weight across municipalities is not significantly affected by the diverging shares of EVs, the average life cycle GHG emissions are (figure 4(e)). The national average peaked around 2010, dipping below the 2000s average by 2021. However, the average life cycle GHG emissions for a car located in many municipality categories was still above the 2000 average, and the emissions started decreasing with some years of delay.

The highest average life cycle GHG emissions in 2022 are in the municipalities with the lowest shares of EVs (figure 4(f)). The unequal spatial distribution of EVs is therefore associated with an unequal decrease in average life cycle GHG emissions.

Bergen, the frontrunner of EV adoption has been keeping the average curb weight below the national average. Thus, the average life cycle GHG emissions in

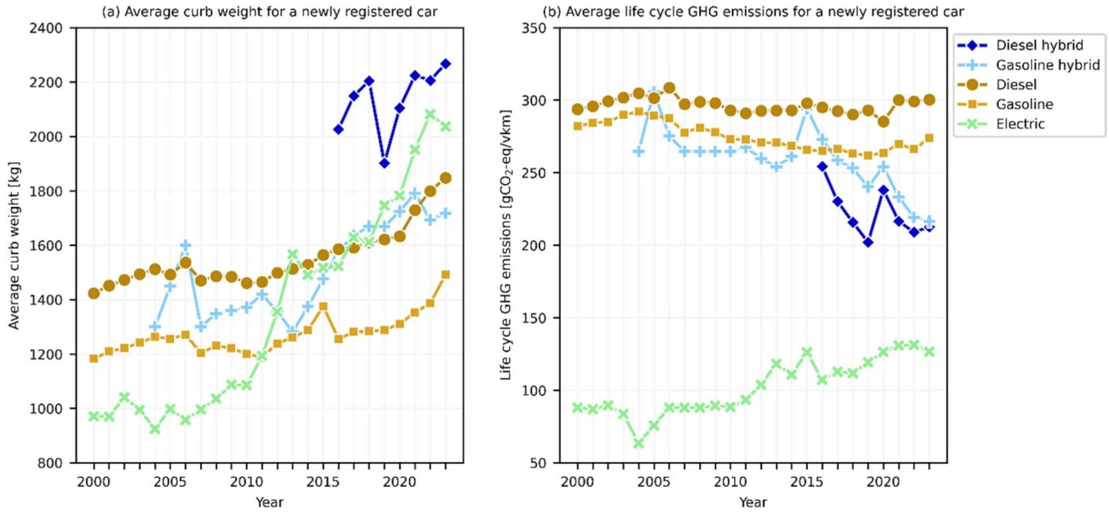

Figure 2. (a) Average curb weight and (b) average life cycle GHG emissions for a newly registered car per powertrain between 2000 and 2023.

Bergen are well below the national average, and lower than in Oslo and Trondheim.

Even if these three large municipalities have a significant share of EVs, the shares vary by district (figure 5). There is a trend of higher average curb weight with higher shares of EVs, but this is not the only factor, as there are some districts with a low share of EVs and yet a high average curb weight. From visual inspection, we note that EV shares and average life cycle GHG emissions are generally somewhat higher and lower, respectively, in more wealthy districts. These two variables, however, do not appear to be correlated with population density of districts.

There is a strong negative correlation between EV shares and life cycle GHG emissions (figure 6(a.1)). In densely populated municipalities, more frequently located in the southern and coastal parts of the country (figure 6(b)), the share of EVs is higher (figure 6(a.7)) and the average life cycle GHG emissions are lower (figure 6(a.8)). Municipalities with larger shares of EVs are closer to a large municipality (figure 6(a.4)) and are also associated with a higher median income (figure 6(a.2)) explaining why wealth shows moderate negative correlation with life cycle GHG emissions (figure 6(a.3)).

4. Discussion

4.1. Trends and spatial characterization of EV adoption

We have shown that EV adoption and associated life cycle GHG emission reductions are not uniformly distributed which points at rural-urban differences. EVs penetrated densely populated areas including cities and their sub-urbs, whilst rural areas lagged (findings in line with [14, 35]). Many EV-promoting policies targeted urban areas and their commuters, such as toll exemption for EVs [36]. While exemptions are being replaced by discounts, the effect is still noticeable. Among the top five municipalities with the highest shares of EVs are Askøy, Bærum and Malvik, located close to Bergen, Oslo and Trondheim, respectively. In these municipalities, commuters benefited from toll exemptions, or other commuting ‘privileges’ [14]. The median income in Askøy, Bærum and Malvik is also around 20%–30% higher than the median income in Bergen, Oslo and Trondheim [31], illustrating the role of income in EV ownership [37].

There are also spatial differences in EV ownership within municipalities. In specific neighborhoods, more than half of the vehicles are electric. Different aspects can potentially explain these differences, such as income, the possibility of charging the car at home [38, 39], access to public charging stations [15, 40, 41], or social norms [42].

Linking the EV incentives with the spatial and temporal trends in EV ownership and life cycle GHG emissions could constitute future research work for understanding their effectiveness and efficiency. New tailored policies targeting geographic locations where EVs are not popular could speed up mobility decarbonization [11] and are likely necessary to achieve further climate change mitigation.

4.2. EVs: a decarbonization option?

The European Union (EU) has set strict CO_2 emission targets for the direct emissions of new passenger cars: from 2030, new cars should emit less than 49.5 $gCO_2\ km^{-1}$ [43]. Norway has set even stricter targets, aiming for all new private cars in 2025 to be electric [44]. In Norway, the average use phase GHG emissions for newly registered vehicles decreased by 89% between 2000 and 2023 (from

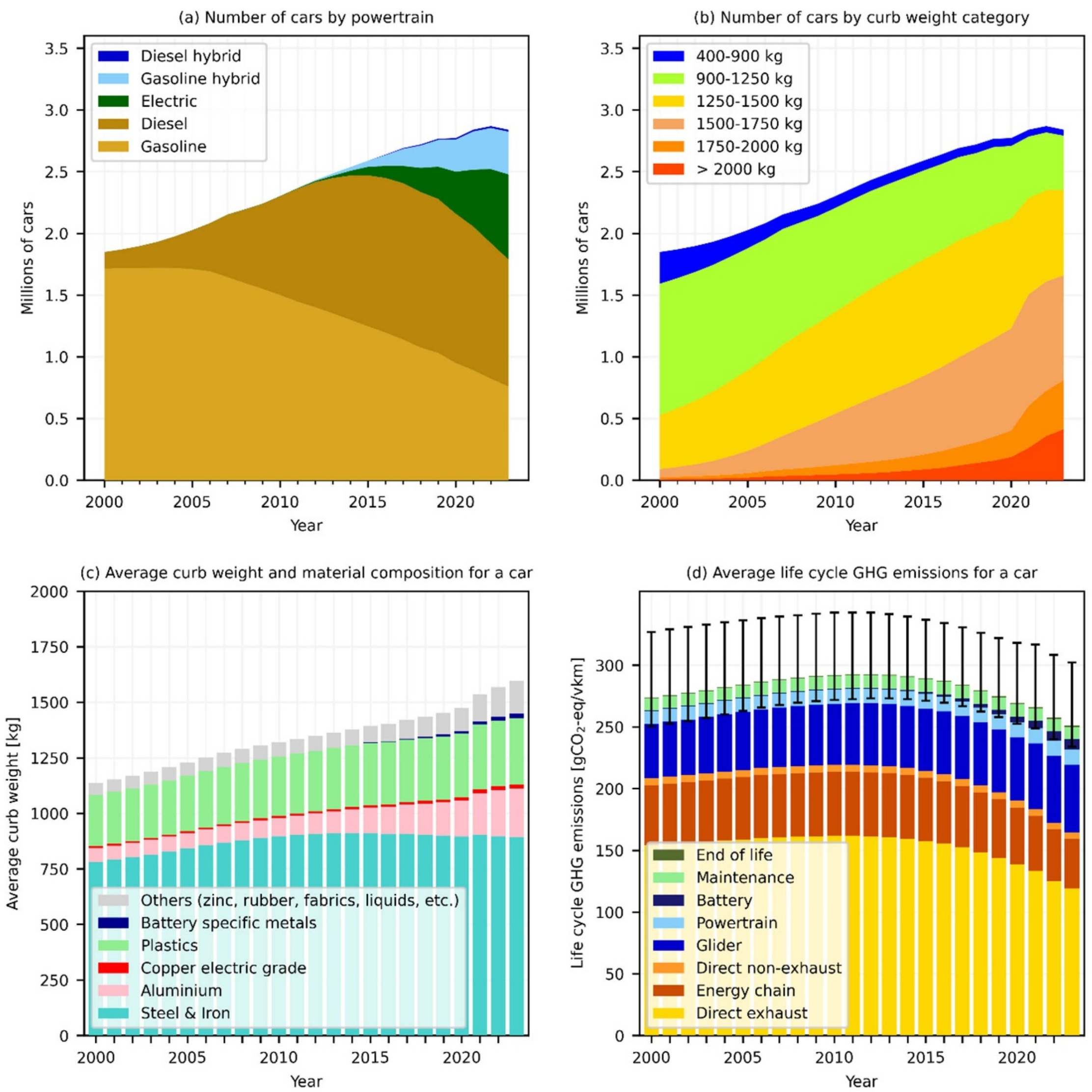

Figure 3. Description and characteristics of the vehicle fleet between 2000 and 2023 in Norway: (a) number of cars by powertrain, (b) number of cars by size (the bottom value of the range is excluded except for the first range 400–900 kg, the top value of the range is included), (c) average curb weight and material composition for a car, (d) life cycle GHG emissions per vehicle-kilometer averaged across the car fleet.

164 to 19 gCO_2-eq vkm^{-1}) (figure 1(d)) and are, therefore, well below the European targets for 2030. However, these use-phase emissions do not account for the component-related emissions, which have increased by 81% since 2000 (from 58 to 104 gCO_2-eq vkm^{-1}) (figure 1(d)). A life cycle perspective is therefore necessary to provide an overview of climate mitigation potential and trade-offs of EVs. In this regard, the EU plans to release guidelines for accounting for upstream emissions by the end of 2025 [45].

Under the United Nations Framework Convention on Climate Change (UNFCCC), Norway is reporting territorial emissions [46]. Hence, Norway does not account, in its road traffic emissions, for production-related emissions occurring abroad. This, combined with a decarbonized electricity grid (about 30 gCO_2eq kWh^{-1} [47]) offers additional motivation for electrifying road transport. We estimated (details in section S3.5 in SI S1), using average yearly driving distance [48], that total vehicle direct emissions in 2023 were 1.2 $MtCO_2$-eq lower than in 2014 (−24%), whilst outsourced emissions of newly registered vehicles to vehicle producing countries increased by 0.8 $MtCO_2$-eq (+40%). Reduced direct emissions thus partly led to increased production emissions that Norway does not report to UNFCCC.

We have shown the scale and speed of Norway's EV transition, how it has reduced direct emissions and the trade-offs on increased upstream emissions. Reducing life cycle GHG emissions beyond the use phase requires decarbonizing material production and manufacturing [49, 50], limiting battery capacity [24, 51], material efficient lightweight designs [52], lifetime extension [53], or material circularity [54]. EV batteries used for short-term energy storage may also offer benefits for renewable electricity grid stability and flexibility [55]. Norway's shift towards electrified personal mobility will continue towards 2040

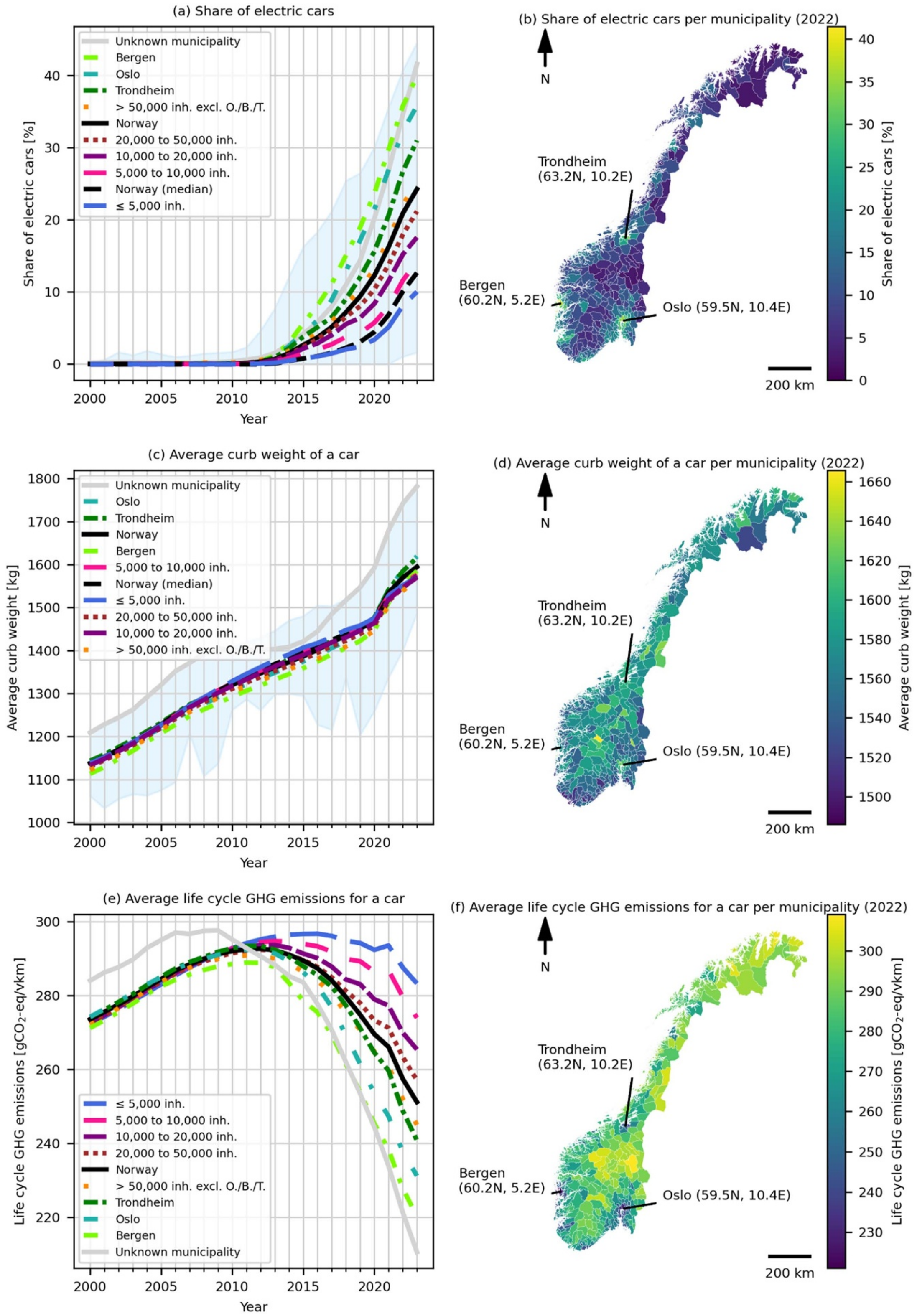

Figure 4. [Right column—fleet from microdata.no] description of historical vehicle fleet in Norway per municipality category and [left column—fleet from Geodata] description of 2022 car fleet in Norway per municipality: (a) and (b) share of electric cars; (c) and (d) average curb weight of a car; (e) and (f) average life cycle GHG emissions for a car. Vehicles under 'Unknown municipality' refer to vehicles mostly owned by companies/organizations, but also to a smaller extent unknown owners or owners living outside Norway. The light blue areas in quadrants (a) and (c) represent the range of values encompassing all municipalities. Due to data extraction constraints from microdata.no, it was not possible to extract the necessary data to produce such graphic for the life cycle GHG emissions in quadrant (e). Detailed explanations on how each of these graphics have been produced can be found in section S3 in SI S1.

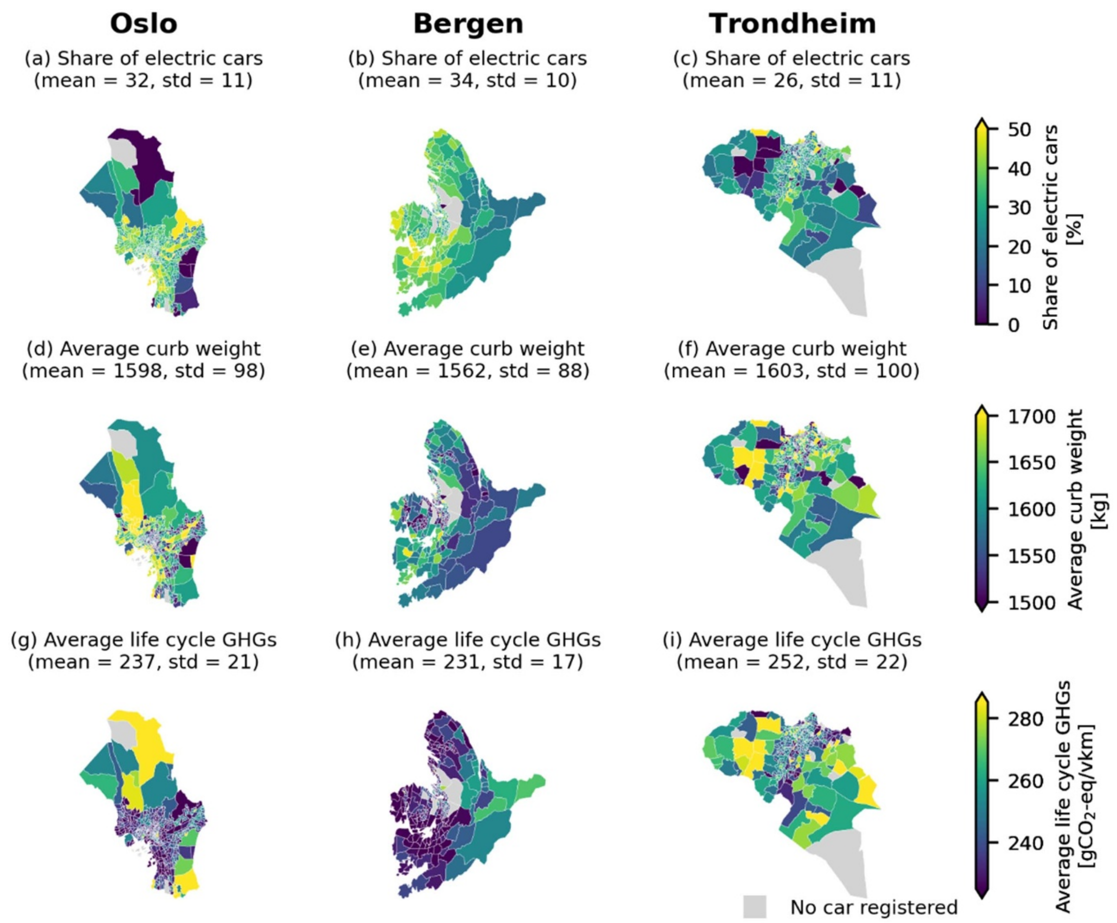

Figure 5. Car fleet description in the three most populous municipalities in Norway (Oslo, Bergen, Trondheim) in 2022: (a)–(c) share of electric vehicles per district; (d)–(f) average curb weight per district; (g)–(i) average life cycle GHG emissions per district. Mean and standard deviation values are provided for each of the municipalities and indicators.

[56, 57]. Utilizing sustainably produced biofuel as a transitional fuel in ICE vehicles during the phase-out period can provide additional climate change mitigation [57–59].

4.3. Limitations and uncertainty

We retrieved the stock of vehicles between 2000 and 2023 from microdata.no. However, this dataset presents some discrepancies and uncertainties. First, before 2016, hybrid vehicles were registered as gasoline/diesel vehicles. We attempted to correct these data (section S1.2.3 in SI S1), but the number of hybrid vehicles before 2016 should still be considered with caution. Second, between 2020 and 2021, we observe that the number of vehicles of a certain registration year and fuel type belonging to certain size categories (based on curb weight) suddenly increased/decreased. These inconsistencies come from changes in curb weight registration [60]. We tested (sections S1.2.5 & S4.1 in SI S1) if these discrepancies are not affecting our main results and conclusions. Lastly, we compared the stock of vehicles for 2022 between Geodata and microdata.no. (section S1.2.4 in SI S1) and found that the datasets are rather consistent in shares of each powertrain despite differences in the total stock (the stock of cars in Geodata is 6% lower than in the three main datasets based on microdata.no).

The life cycle GHG emissions generated by *carculator* encompass uncertainties [24]. Based on the Ecoinvent database, the inventory of the supply chains and end-of-life are not region-specific, and we used the package's default parameters (e.g. for efficiency, battery size and range). Limitations are hence carried by our results. Future research could account for geographic origin of vehicles in the Norwegian fleet and fate of batteries [61]. The stochastic mode in *carculator* was used to define uncertainty ranges on the GHG emissions. Other sources of uncertainty exist, but they are not captured in this research.

Life cycle GHG emissions were calculated using the same total yearly distance driven by all cars, independently of their powertrain. SSB reports that EV and hybrid vehicles were, on average, driven for 20%–84% longer distances in 2023 than ICE vehicles, whose average yearly distance driven shows a decreasing trend [62]. This could be due to people owning several vehicles and using EVs frequently for shorter distances (e.g. EV buyers keeping their old cars [14]),

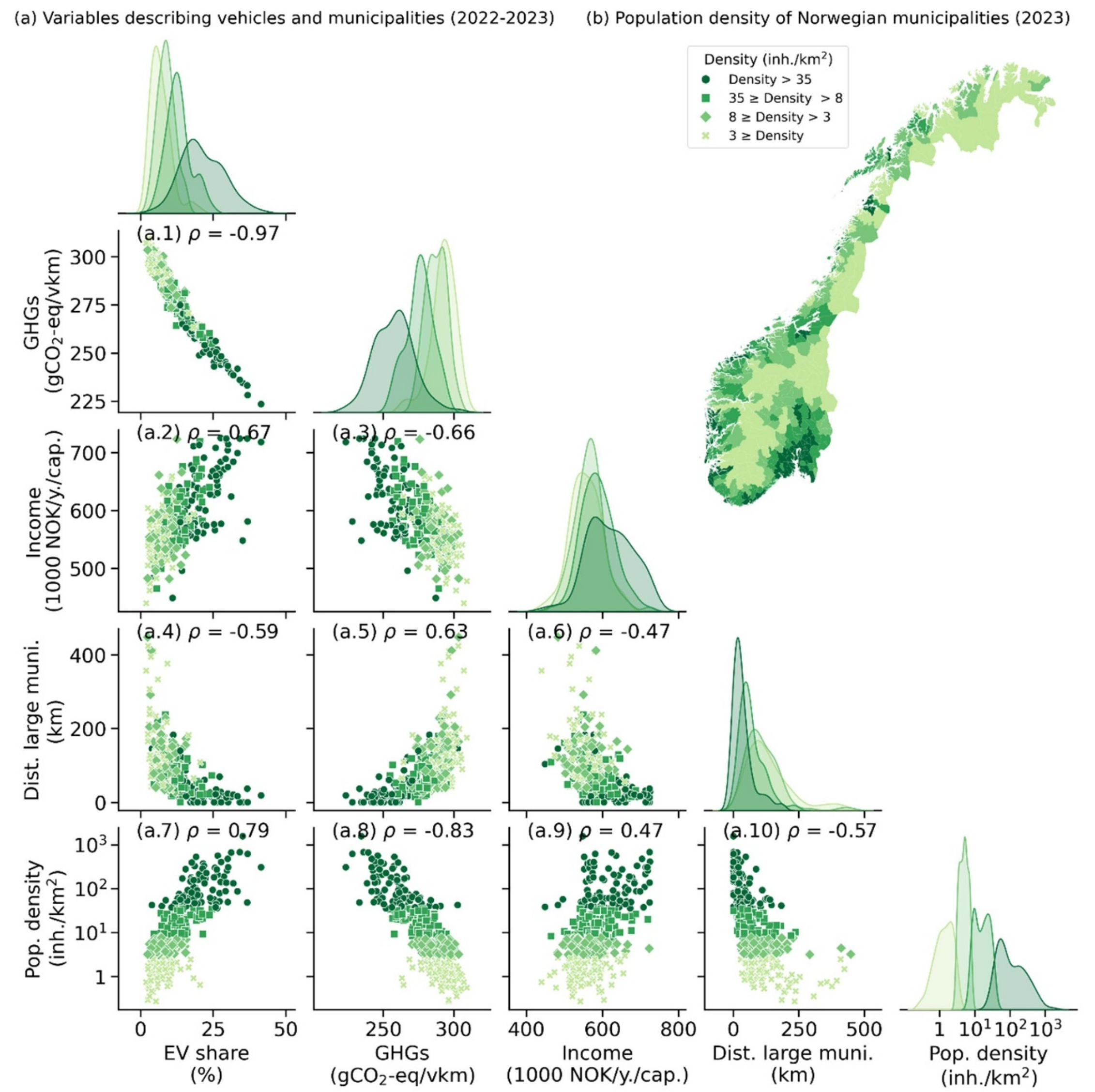

Figure 6. Scatter plots of passenger vehicles and socio-economic characteristics of municipalities (each dot in the pair plot represents a municipality): (a) visualization of variables describing vehicles and municipalities (all variables are for 2022 except population density, which is for 2023). Correlations are measured by the Pearson correlation coefficient ρ. The population density is displayed using a logarithmic axis; (b) population density of Norwegian municipalities in 2023 (categorized by quartiles). A description of the variables and a linear regression analysis are available in section S3.4. in SI S1.

a faster pay off of EVs with high capital cost but lower operating cost, or the ICE fleet aging and being used less frequently. The average age of discarded vehicles has remained around 18 years for the past ten years [63] (close to the Western European mean [64]), indicating that EVs adoption has not yet affected the age of discarded vehicles. A sensitivity analysis on the lifetime in total kilometers and lifetime in years, parameters used in *carculator,* is conducted showing limited effects on the changes in fleet-average life cycle GHG emissions per kilometer driven since 2000 (section S4.3 in SI S1).

4.4. Implications and outlook

Incentives to adopt EVs have had visible effects in Norway. The share of EVs in the fleet has multiplied by 16 since 2014, EVs constitute more than four out of five newly registered cars, and the reduction of total tailpipe emissions of the fleet is significant (24% decrease between 2014 and 2023). This reveals a rapid shift within the past ten years and creates a unique EV situation in Norway. However, fleet-average life cycle GHG emissions per km driven have decreased only by 8% since 2000. This small decline reflects the latency of GHG emissions given the slow turnover of the fleet, in line with literature [56], and the increasing component-related emissions of newly registered vehicles, mitigating the apparent success of EV incentives.

Whilst the strong EV policies made Norway a world-leading EV adopter, it also led to revenue losses that had to be compensated by other income [65, 66]. Researchers estimated the cost of reduced CO_2 emissions to be of several thousands of Norwegian

Kroner per tonne of tailpipe or life cycle GHG emissions reduced [67–70]. Tax exemptions were applied to all types of EVs, with a higher economic value for heavier, more expensive EVs. We have shown that the average weight of vehicles has been increasing over the last years despite the use of lightweight aluminum (as opposed to steel) for car production [53, 71]. EVs gained the most weight, probably driven by an increase in battery range, leading to higher component-related emissions. Even if no causal relationship is studied, winter conditions affecting the range [72] might have encouraged buyers to choose vehicles with longer driving distance and heavier batteries, and a general trend towards the adoption of larger EVs was most likely facilitated by the incentives. Some of the most attractive incentives have been revised, reflecting the increasing maturity of the EV market. For instance, a weight-based vehicle tax introduced in January 2023 [34] incentivizes lighter vehicles [73]. In addition, the value added tax exemption for EVs became applicable only for the first 500 000 Norwegian Kroner (about 45 000 US. dollar) of the selling price [74]. By introducing a threshold on vehicle price, expensive EVs are now partially taxed, reducing the incentives for wealthy households to purchase expensive EVs and benefitting from the full VAT exemption.

While we show a positive correlation between median income and the share of EVs per municipality, this remains an observation. Investigating the role of income requires further statistical analysis [75, 76] and should be considered when designing EV incentives, which is beyond the scope of this research.

It is important to highlight that the incentives have been technology-focused, not questioning the use of private passenger vehicles leading to more vehicles in the stock and an increasing number of km driven [77]. Some of the incentives (e.g. free parking and tolls, use of the bus lanes) were most likely encouraging more driving, getting an EV as an additional car, and replacing alternative transport modes [70, 78]. Consequently, car-related issues such as traffic jams or particulate matter pollution from tires (especially winter tires) and break wear were left unaddressed [67, 79]. These non-exhaust emissions bear significant public health risks worsen by the increasing weight of vehicles which increases such emissions [80–85], highlighting that the EV incentives have been focused on GHG emissions.

As we demonstrated with electrification of the fleet, policies take time to show significant changes at the fleet level, even with attractive policies. However, we could still observe a reduction in use-phase emissions and an increase in component-related emissions, underscoring the insufficiency of focusing only on direct emissions when trying to understand the role of EVs in mitigating GHG emissions. The concentration of EV ownership in urban and peri-urban areas indicates that an effective GHG mitigation likely requires tailored policies considering spatial differences.

Data availability statement

We used microdata.no (www.microdata.no/en/), a platform to extract Norwegian microdata; it can be used by employees and students at universities and colleges, approved research institutions (recognized by the Research Council of Norway or Eurostat), ministries, and directorates (more information: www.ssb.no/en/data-til-forskning/utlan-av-data-til-forskere). The code used to extract the data from microdata.no is available on Zenodo (https://doi.org/10.5281/zenodo.14697508) along with the three datasets generated based on these extracted data. Data used for the figures are also found in the Zenodo repository. Some of the raw data used in this study are from Geodata (www.geodata.no/), restrictions apply to the availability of these data, which were used under license for this study. The archetypes of passenger vehicles originate from the CIRCOMOD project (https://circomod.eu/) and can be obtained upon reasonable request. The codes for analysis of the results are also available upon reasonable request.

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Conflict of interest

The authors declare no conflict of interest.

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Author contributions

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